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Patterns of innovation and organizational demography in emerging sustainable fields: an analysis of the chemical sector

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Abstract

This paper examines the patterns of environmental innovation in the chemical sector and focuses in particular on detecting whether the rise of sustainable chemistry technologies (SCT) has stimulated the emergence of new organizations. This question is important to assess the extent to which SCT are sustaining the technological advantage of industry incumbents or are creating opportunities for new firms aspiring to develop radically new environmental innovations. We found that SCT still represent a relatively low proportion of chemical technologies and that they have not stimulated, in a significant way, the emergence of new firms. However, the importance of new firms has grown in the last years and their technologies seem to have a higher potential of radicalness than incumbents' technologies. This indicates that, although incumbents' advantage remains strong, a small group of young firms has started to weaken such advantage. Moreover, the important role played by research organizations in generating SCT may signal that technological opportunities are expanding and that some governments, in particular the US government, are committed to develop SCT. These results suggest that, if supported by effective policies, technological ferment in the field, which at the present appears still limited, has a potential of growth.

Keywords: Radical environmental innovation; Organizational demography; Technological ferment; Chemical sector; Patent analysis.

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1. Introduction

Our current modes of production and consumption have created severe problems in terms of both depletion of natural resources and environmental pollution, and therefore are widely considered unsustainable. Environmental innovation has the potential to trigger a transition toward more sustainable economies. Such potential, however, critically depends on the ability to generate radically new environmental technologies, capable to achieve significant environmental benefits. Given the magnitude and pervasiveness of environmental problems we are facing, it is likely that incremental environmental improvements in existing technologies will not suffice to cope with prevailing sustainability challenges (Kemp et al., 1998; Dosi and Grazzi, 2006; Markard et al., 2012). Yet, developing radical technologies often requires large, long-term investments, and, above all, it is a risky process because of the high uncertainty surrounding the technological and commercial output of these innovations. Moreover, by definition, radical innovations have a strong disruptive impact on exiting technologies, competences, organizational structures and even, in some cases, on broader economic and institutional structures. Therefore, they may meet the resistance of vested interests (Kemp et al., 1998).

Using patent data, this article analyzes the patterns of environmental innovation in the chemical sector, a sector that is highly important for environmental sustainability due to both its economic relevance (in terms of world economic growth and employment) and its strong environmental impact (polluting and nonrenewable feedstocks like petroleum, toxic wastes, non degradable products, industrial accidents). In this context, we are especially interested in detecting whether the rise of sustainable chemistry technologies (SCT) is stimulating the emergence of new organizations, namely new firms and research organizations (universities and government agencies). Answers to this question are important to assess the extent to which SCT are sustaining the technological advantage of incumbent firms, strengthening their position in the industry, or are disrupting established technologies and competences, creating opportunities for new firms aspiring to develop radically new environmental alternatives.

Although with different perspectives, various theoretical approaches (Anderson and Tushman, 1990; Christensen, 1997; Kemp et al., 1998; Breschi et al., 2000; Markard et al., 2012) associate the emergence of new firms to an era of “technological ferment”, a turbulent period characterized by high technological opportunities, the “creative destruction” of established technologies, the erosion of incumbents' advantage and the emergence of radically new products

and processes. The absence of new organizations and the dominance of incumbents is instead associated with improved variants of existing products and processes, incremental or competence-enhancing changes, sustaining innovations and established regimes. The general explanation advanced by these studies is that incumbents possess specific knowledge (Breschi et al., 2000), competences (Anderson and Tushman, 1990), complementary assets (Geels, 2011), managerial practices and values (Christensen, 1997) that make either difficult or disadvantageous for them investing in radically new technologies. Leading firms may not have the competences for developing radically new technologies because they are burdened with the legacy of prior technologies and ways of operating (Tushman and Romanelli, 1985). Moreover, incumbents may not be interested in stimulating a competing technology and may not be willing to risk their core competencies, technologies and production facilities becoming superfluous (Kemp et al., 1998).

Based on these studies, we propose that observing a high number of new firms engaged in the development of SCT may signal that we are experiencing a period of technological ferment, characterized by exploration, experimentation and competition among different technological alternatives that try to break with exiting knowledge and create radically new environmental innovations. A growth of university innovative activity also may be symptomatic of technological turbulence, as universities develop more basic technological knowledge (Trajtenberg et al., 1997), which increases technological opportunities and lowers barriers to entry (Malerba, 2002). A sustained innovative activity of government agencies should signal the support of involved governments to develop SCT, which may be critically important for the emergence of radical innovations too. On the contrary, the dominance of incumbents' technologies should indicate that we are experiencing a period of stability, characterized by incremental changes and the “creative accumulation” of existing technologies, capabilities and resources. In this scenario, incumbents elaborate and incrementally adapt their current products and processes in order to reduce their environmental impact.

To obtain systematic evidence on the emergence of new organizations in the field of SCT, we first build an original dataset of patents relating to SCT, and analyze the main trends emerging from patent statistics. We then use network analysis algorithms to map the main clusters of SCT and identify the technological areas where organizations are concentrating their research efforts. Finally, we detect the demography of organizations that generated SCT clusters. With organizational demography we intend the organization type (public versus private), its age,

nationality, and some properties of their knowledge base that are expected to capture the degree of radicalness of their technologies. This allows us to determine the respective role played by incumbents, new firms and research organizations in generating SCT, and to provide an indication of their respective potential to develop radically new environmental innovations. The rest of the paper is organized as follow. Section 2 is an overview of the theoretical approaches outlined above, the main characteristics of the chemical sector and the most important sustainable initiatives in the chemical sector. Section 3 illustrates data and methods. In section 4, we present and discuss the main trends emerging from patent statistics, the analysis of SCT clusters and the study of organizational demography. In section 5 we conclude.

2. Background

2.1 Background literature

Innovative activities involve a variety of actors, including large incumbents, new and usually smaller firms, as well as other types of organizations such as universities and government agencies. The important role played by universities and government agencies as major source of new scientific and technological knowledge has been highlighted by many studies (e.g., Nelson, 1993). Compared to firms, universities generate more basic technological knowledge (Trajtenberg et al. 1997), which increases technological opportunities and lowers barriers to entry (Malerba, 2002). As to firms, a long tradition starting with Schumpeter (1911, 1942) has studied the respective roles and capabilities in innovative activities of incumbents and new firms. Schumpeter first highlighted the role of individual entrepreneurs in generating innovation and creating early industrialization (Schumpeter, 1911), while later concluded that large companies, through their in-house R&D laboratories, would assume an even more important role compared to new and smaller firms (Schumpeter, 1942).

Building on these ideas, a number of studies have focused on analyzing the two basic patterns of innovation highlighted by Schumpeter, namely Mark I and Mark II (Malerba and Orsenigo, 1996; Breschi et al., 2000). Schumpeter Mark I is a turbulent environment characterized by the “creative destruction” of established technologies and business practices. In this context, innovations are mainly generated by new innovative firms, which finally end-up to replace

incumbents: “new entrepreneurs come in an industry with new ideas and innovations, launch new enterprises which challenge established firms and continuously disrupt the current ways of production, organization and distribution” (Breschi et al., 2000). Schumpeter Mark II is instead a stable environment characterized by the “creative accumulation” of existing technologies, capabilities and resources. Here, the main players are large established firms, which benefit from the consolidation of their accumulated knowledge, creating high entry barriers to new firms. In sum, Mark I is characterized by the emergence of disruptive innovations, the entry of new innovators and the erosion of the competitive and technological advantage of the established firms, while Mark II is associated with more incremental or sustaining innovations and the dominance of established firms.

According to these studies, the observed patterns of innovative activities within a sector largely depend on the specific characteristics of involved technologies, including technological opportunities, appropriability of innovations and cumulateness of technical advances (Malerba and Orsenigo, 1996). Early in the history of an industry or in the presence of major technological and market discontinuities, Mark I will tend to prevail because in those circumstances technological opportunities are high, while appropriability and cumulateness are low (Malerba, 2002). Therefore, barriers to entry are low. On the contrary, when the industry matures and technological change follows well defined trajectories, economies of scale, learning curves, barriers to entry and financial resources become important (Malerba, 2002). More recently, Fontana et al. (2012) have showed that breakthrough inventions are more likely to emerge in “turbulent” Schumpeter Mark I type of contexts.

The challenges of incumbent firms in face of radical innovation are also analyzed by the technological discontinuities approach (Tushman and Anderson, 1986; Anderson and Tushman, 1990) and the disruptive innovation approach (Rosenbloom and Christensen, 1995; Christensen, 1997). According to the first approach, technology evolves through long periods of incremental change punctuated by technological discontinuities, which can be either competence-destroying or competence-enhancing. Competence-destroying discontinuities require fundamentally new skills and know-how to be generated and focus on developing new products that eventually replace existing ones. On the contrary, competence-enhancing discontinuities build on existing skills and know-how, focusing on revitalizing existing products with complementary technologies. Both discontinuities introduce variation in a product class, triggering a period of technological ferment

characterized by experimentation, competition among technological variants and great uncertainty about the winning technology. The era of ferment culminates in the selection of a single dominant configuration of the new technology, i.e., the dominant design, which is then improved during the subsequent period of incremental change.

Technological discontinuities have a marked different impact on industry structure. As competence-destroying discontinuities require fundamentally new skills and know-how, competences that brought established leaders to preeminence are rendered largely obsolete (Anderson and Tushman, 1990). New entrants, founded to exploit the new technology, gain market share at the expense of formerly dominant firms, which are burdened with the legacy of prior technologies and ways of operating (Tushman and Romanelli, 1985). On the contrary, as competence-enhancing discontinuities build on existing skills and know-how, incumbents are in the best position to initiate and exploit new possibilities opened up by this kind of discontinuity. Therefore, competence-enhancing discontinuities increase barriers to entry and tend to consolidate industry leadership. Moreover, competence-destroying discontinuities induce increased environmental turbulence and have a greater potential of growth than competence-enhancing discontinuities (Tushman and Anderson, 1986).

While the technological discontinuities approach focuses on firms competences, the disruptive innovation approach focuses on customer and market dynamics. Christensen's analysis is based on the concepts of disruptive and sustaining innovation. Sustaining innovations, which represent most of the innovations in an industry, improve the performance of established products along the dimensions of performance that mainstream customers value. On the contrary, disruptive innovations underperform established products in mainstream markets, but bring to a market a very different value proposition than had been available previously (Rosenbloom and Christensen, 1995; Christensen, 1997). Though disruptive innovations initially can only be used in smaller, lower-performance and lower-margin markets, eventually they can completely replace established products as with time they will be able to both deliver sufficient performance on the old products attributes and add some new ones.

In this context, industry leaders, which are excellent at developing sustaining innovations, often fail when confronted with disruptive innovations. This is because incumbents are focused on the needs of their current customers, who generally don't want products based on disruptive technologies, and invest aggressively for increasing the performance of mainstream products,

which eventually will overshoot the performance that mainstream markets demand. Moreover, because of their size, incumbents have to target large, high-performance, high-margin markets. Hence, most companies which have developed strong capabilities for satisfying their current customers and identifying new products that promise high profitability do not possess the capabilities required for successful investing in high-risky and uncertain disruptive innovations, where market data are unreliable and where neither revenues or costs can be known in advance (Christensen, 1997). Therefore, in Christensen's analysis, small entrant firms enjoy a powerful advantage compared to incumbents: they have the incentives and the competences for developing disruptive innovations, while established leaders, by definition, do not: because disruptive technologies rarely make sense during the years when investing in them is most important, conventional managerial practices and values at established firms will force a disruptive technology to fit the needs of current, mainstream customers (Christensen, 1997).

The respective role played by incumbents and new firms in innovative activities is also analyzed, with a specific focus on environmental innovation, by sustainability transitions studies (Markard et al., 2012; Geels, 2011; Kemp et al., 1998). The core analytical issue of sustainability transitions research is how to promote and govern a fundamental transformation towards more sustainable modes of production and consumption (Markard et al., 2012). The emergence of radically new environmental innovations is the main driver of such fundamental changes, which, nevertheless, are difficult to achieve because existing modes of production and consumption, i.e., existing regimes, are characterized by strong path-dependencies and lock-ins, including established technologies, scale economies, sunk investments in machines, infrastructures and competencies. Moreover, established technologies are highly intertwined with user practices and life styles, business models, regulations, organizational, institutional and political structures (Markard et al., 2012). For those reasons, existing regimes tend to favor stability: they can accommodate incremental changes along established trajectories, but have problems in driving radical technological innovation, thus preventing sustainability transitions (Kemp et al., 1998).

In this perspective, incumbent firms are mainly viewed as conservative forces, the “regime actors”, which tend to defend and stabilize existing systems by resisting to radical change and focusing on incremental environmental innovations. This is because incumbents possess “complementary assets”, including specialized manufacturing capability, experience with large scale test trials, access to distribution channels, service networks and complementary technologies

(Geels, 2011). At the opposite, new firms are viewed as the initial promoters of sustainability transitions. They act at “niche level” to explore and experiment radically new alternatives to existing technologies. Niches are small, dynamic and low-structured “protected spaces” that nurture interactive learning processes and shield new technologies from premature competitive pressures (Smith and Raven, 2012). Proposing a typology of four transition pathways based on involved actors, Geels and Schot (2007) envisage a more active role of incumbents when niches are not well developed. However, when niches are developed, radically new environmental innovations emerge leading to a new regime, and incumbents are eventually replaced by niche actors.

In short, although with different perspectives, the studies discussed above share the common vision that incumbents possess specific knowledge, competences, complementary assets, managerial practices and values that make either awkward or disadvantageous for them investing in radically new technologies. Therefore, there seem to be sufficient theoretical support for the hypothesis that the emergence of new organizations is indicative of those periods of technological ferment preceding radical changes and that, at the contrary, the dominance of incumbents is an indicator of technological stability based on the exploitation of existing trajectories of change. The long history of the chemical industry also provides support for such hypothesis. As highlighted in Cesaroni et al. (2004), each of the major innovations of the chemical industry – the synthetic-dyestuff model in the second half of XIX century, the polymer chemistry since 1920s and the unit operation (chemical engineering) in the years before the Second World War – has triggered the emergence of new players. The rise of biotechnology since the mid-1970s can also be considered as a technological discontinuity for the chemical industry, and it also spurred the creation of new firms (Rothaermel, 2001). On the other hand, as outlined below, chemical companies have showed great continuity in their production and innovative activity. This suggests that they have been often able to successfully respond to radical innovations and to integrate them within their existing competences (Ansari and Krop, 2012).

2.2 The chemical sector

The chemical sector is an old and large sector. Its origins date back to XIX century, with the emergence of British and German dye-stuff manufacturers, and it is today one of the largest manufacturing industries in the US, Europe and Japan. The sector has acquired a growing importance in many emerging countries as well, in particular China and India, which in the last decade (2001-2011) have overtaken Europe and US in terms of market shares (Cefic, 2013). The chemical sector is also highly heterogeneous. It is composed of at least four different subsectors: 1. basic chemicals (polymers, basic industrials, bulk petrochemicals and intermediates); 2. life sciences products like pharmaceuticals, diagnostics products and biotechnology products; 3. specialty/fine chemicals, which include electronic chemicals, industrial gases, adhesives, coatings, industrial cleaning chemicals and catalysts; 4) consumer products like soaps, detergents and cosmetics (Gavrilescu and Chisti, 2005). Basic chemicals are low value-added products that are manufactured in massive quantities and are used to produce more sophisticated and differentiated products like life sciences products and specialty chemicals (Cesaroni et al., 2004).

The chemical sector is a science-based and R&D intensive sector. Chemical innovation has always relied on the application of scientific knowledge to the discovering of new products and processes. All modern chemistry is basically based on the scientific understanding of the chemical structure of raw materials, which is used to synthesize new materials with better properties. For this reason, universities and other research organizations have always played an important role in fueling chemical innovation. As to private firms, the chemical sector has a long and important tradition of in-house R&D, which typically takes place in the laboratories of large, established, now multinational firms. Moreover, due to the high fixed costs of plants' setting and product development, the chemical sector is capital-intensive, and, as a consequence, it has high barriers to entry and exit.

The prevailing industry structure is made of relatively few large players, together with several smaller and more specialized companies. Large players are established firms, which benefit from economies of scale and scope, and have showed a great continuity in their production and innovative activity (Oltra and Saint-Jean, 2007). Many of these firms have been founded in the XIX century, have been leaders in their own domestic markets up to the 1980s, and now act as global oligopolies in their specific subsectors (Cesaroni et al., 2004). Smaller firms are specialized in the engineering of the new plants (process technology), in the fine and specialty chemicals, and, more recently, in biotechnology.

2.3 Sustainable Chemistry

The severe impact of chemicals on human and environmental health, as well as the expected increase of energy demand and depletion of fossil resources, has increased the interest, in the last decades, for developing a more sustainable chemistry. Such an interest has materialized in a number of government initiatives that taken the form of environmental regulation and government programs. In the US, the Pollution Prevention Act (1990) formalized the need to adopt pollution prevention policies rather than command and control policies, and opened financial means to the Environmental Protection Agency (EPA) for launching new programs aimed at developing more sustainable chemical technologies. The EPA started the Green Chemistry Program officially in 1993 and this program continues to promote green chemistry with research grants and education. In Europe, the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation, which entered into force in 2007, strengthens the former legislative framework on chemicals of the European Union, in particular by asking industry for assessing and managing the risks posed by chemicals and for providing appropriate safety information to users. Two industry groups, Cefic and EuropaBio, along with the European Commission have established the European Technology Platform for Sustainable Chemistry (SusChem) to encourage R&D in Europe (OECD, 2011). Similar initiatives have been taken in many other countries, including Japan and Canada. Moreover, a number of governments provide financial support (grants and tax preferences) for R&D expenditures relating to sustainable chemistry, implement green public purchasing policies and offer incentives for the adoption of green chemistry products (Nameroff et al. 2004; OECD, 2011).

Universities, often supported by government initiatives, have made an important contribution to the development of sustainable chemistry. Scholars have established specialized networks for the purposes of information dissemination and education (e.g., the Green Chemistry Network, the Japanese Green and Sustainable Chemistry Network), specialized research centers (e.g., the Green Chemistry Institute) and scientific journals (*The Green Chemistry Journal* and *ChemSusChem*). Many renowned chemical journals have dedicated special issues to sustainability research and sustainability has been incorporated into the curricula of many standard chemistry courses. As to private firms, little evidence has been provided and it is mainly anecdotal evidence (Sanderson, 2011; OECD, 2011). As unique exception, Nameroff et al. (2004) try to quantify the extent of adoption of green chemistry practices by using US patent data. The authors found that many industrial sectors are not rapidly moving toward more sustainable practices and processes.

However, this study mainly focuses on the Green Chemistry approach promoted by the US EPA² (it does not take into account, for example, the developments relating to biomass) and on a relatively restricted period of time (patents granted between 1983 and 2001). In the present work, the objective is to take into account all the main (identified) technological developments relating to the broader field of sustainable chemistry in order to analyze innovation and organizational dynamics.

3. Data and methods

One of the reasons behind the lack of quantitative studies relating to environmental innovation in the chemical sector relies in the difficulties posed by the selection of the relevant dataset of patents. Those difficulties are due to both the high heterogeneity of the chemical sector and the emerging nature of SCT. In this study, we try to overcome such difficulties by putting particular emphasis on selecting and validating the patent search strategy. Since SCT spread among different technological classes and there is not a single set of technological classes that clearly refers to SCT, the dataset has been created by combining keyword search and technological class search. More in particular, after reviewing the scientific literature³ and interviewing experts, we identified the main sustainable chemistry technologies and selected a list of corresponding keywords⁴. We searched for the keyword list on titles, abstracts and claims of patents granted from 1971 to 2011 by the USPTO. In order to minimize the number of irrelevant patents, the keyword search has been limited to patents belonging to the chemical field⁵. Following OECD (2011), we also added a number of technological sub-classes that can be clearly associated with SCT. Finally, a sample of the dataset has been analyzed by an expert and further refined⁶. We obtained a final dataset of 27355 patents, which, we believe, represent a good, although not perfect, indicator of SCT.

2 See Epicoco et al. (2014).

3 We relied especially on Epicoco et al. (2014), OECD (2011), Anastas and Eghbali (2010), Beach et al. (2009).

4 We interviewed Professors Henri Cramail and Daniel Taton (University of Bordeaux I). During the interviews we discussed our preliminary review of SCT and the corresponding keywords, in particular asking to experts to integrate or modify the keywords list. In writing up the keywords list, we also relied on previous patent research filters (Nameroff et al., 2004; OECD, 2011). The main SCT are summarized in the Appendix. To give an indication of the performed search, in the Appendix we also provide an extract of the patent search filter.

5 Following Nameroff et al. (2004), total chemical patents have been selected by including the IPC C, B01 and B04.

6 Enrico Burello (TNO).

To analyze SCT, we created a network of citations among SCT patents and applied to it a clustering algorithm. In this context, each patent corresponds to a vertex of the network and each citation among patents is represented as an arc connecting the citing patent to the cited patent. Technological knowledge is assumed to grow over time by using and expanding existing knowledge. Patents can be thought as a discrete piece of technological knowledge and citations to prior patents can be supposed to represent the technological contribution of preexisting pieces of knowledge. If so, patent citations can be used to map connections among knowledge pieces and to identify patents that are more closely connected with each other than with other patents. To that purpose, we used an algorithm called Island⁷, which identifies in the whole network of patents, all non-overlapping sub-networks (subsets of vertices) that are more closely connected within each other than with external vertices (i.e., patents that do not belong to the same sub-network). However, the Island algorithm is not based on simple citations; rather it uses traversal weights on arcs calculated following the Hummon and Doreian (1989) main path analysis⁸. Those traversal weights measure the importance of paths linking the “oldest” vertices in a citation network to the most recent ones and have been used to calculate longitudinal connectivity among vertices in a network⁹. Using traversal weights, we can define a cluster (or an Island) as a connected sub-network of size in the interval k - K (k and K are the minimum and maximal size of the sub-network, respectively¹⁰), with stronger internal connectivity relatively to its neighborhood (Batagelj, 2003).

Patents contain information such as the organization that developed the invention, its location, the technological fields of the invention and citations to previous documents. We used patent information firstly to detect the different types of organization that generated SCT clusters (new firms, established firms and research organizations), and secondly to assess their potential to generate radically new innovations. To that purpose, using the following measures, we calculate

7 Batagelj (2003); Batagelj et al. (2006).

8 Traversal weights on arcs are calculated using the SPC method. In an acyclic network there is at least one entry vertex and at least one exit vertex. Let us denote with I and O the set of all entries and all exits, respectively. The SPC method assigns to each arc as its weight the number of the different I - O paths passing through the arc. This number is then divided by the total number of paths between entry and exit vertices in the network. This proportion is the traversal weight of an arc. Traversal weights on arcs and vertices are calculated simultaneously, so that traversal weights on arcs always correspond to traversal weights on vertices. See Batagelj (2003) for more details.

9 See for example Mina et al. (2007) and Barberá-Tomás et al. (2011). To our knowledge, traversal weights have been extensively used to identify the main technological trajectory of a given technological domain. However, their application to the identification of technological clusters and involved organizations has only been done, to a smaller extent, by Epicoco (2013).

10 We discard clusters of size smaller than k as ‘noninteresting’ since they are too small, while clusters of size larger than K are too large and contain several themes (Batagelj, 2003).

some properties of organizations' knowledge base that are expected to capture the degree of “radicalness” of involved technologies. The first measure is based on non-patent references (NPR), i.e., citations made by patents to scientific publications and other documents (books, abstracts, proceedings, etc.). NPR are used to proxy the scientific foundations of inventions, the extent to which an invention relies on scientific knowledge (Trajtenberg et al., 1997). A high number of NPR is associated with more basic research (Trajtenberg et al., 1997) and with higher technological opportunities (Von Greavenitz et al., 2013). Following Trajtenberg et al. (1997) we use the number of NPR to calculate a simple index called “SCIENCE”, which measures the predominance of scientific sources as proxied by the number of NPR over technological ones, represented by backward citations to patent documents.

The second and third measures are the number of patent claims and the number of international classes, respectively. The patent claims specify in detail the “components”, or building blocks of the patented invention, and hence their number may be indicative of the “width” of the invention (Hall et al., 2001). The number of international classes cited by the patent proxies the variety of technological fields covered by the patent and it is used to measure the scope or technological diversity of inventions (Lerner, 1994). Patents with higher technological scope are indicative of a more diversified knowledge base (Breschi et al., 2003). Organizations whose knowledge base is rooted in a wider variety of technological fields are expected to be better capable of both identifying new technological opportunities coming from different fields and combining them to develop more complex innovations (Quintana-Garcia et al., 2008; Cassi et al., 2015). Finally, the originality index (Trajtenberg et al., 1997) is used to measure the technological diversity of prior knowledge. It captures whether the patent is based on prior knowledge spread across different technological fields, rather than concentrated in a few technologies (Cassi et al., 2015). The index is based on a Herfindahl index that reflects the dispersion across patent classes of citations made by the patent¹¹. A patent is considered more original if it cites prior art from many rather than few technology classes, hence the larger is the originality index the broader are the technological roots of the underlying research (Trajtenberg et al., 1997). The notion behind this measure is that synthesis of divergent ideas is characteristic of research that is highly original (Trajtenberg et al., 1997). In the literature, the originality index is associated with more radical,

11 This measure is biased downward, especially if the number of backward citations is small, therefore we used the bias-adjusted originality index proposed by Hall (2000).

valuable and even breakthrough patents (Cassi et al., 2015; Rosenkopf and Neckar, 2001; Sterzi, 2013; Arts and Veugelers, 2014).

This methodological approach has of course limitations. The first set of limitations relates to the patent dataset. Despite our efforts to validate the patent search strategy, our dataset may contain a number of irrelevant patents and may have missed some relevant patents. To our knowledge, there is not a way to completely avoid this type of errors. However, the incorporation of practitioners in construct measurement, as has been done in this study, may mitigate the importance of such errors (Nelson et al., 2014). In addition, this study is based on the USPTO dataset, which may be biased towards US organizations. As a consequence the innovative activity of US organizations may be, to some extent, overestimated in our analysis. However, protecting innovations in the US market is important for foreign organizations and US foreign patents remain a good measure of the technological capabilities of foreign countries (Pavitt, 1985). The second set of limitations relates to patents as measure of innovation and technological knowledge. It is very well known that innovative activity is not fully revealed by patenting activity because many patents never reach the market. Most importantly for our analysis, patents are often used for strategic objectives. Therefore organizations may have different propensity to patents, depending on their strategies for protecting innovations. For this reason, patents are also a very imperfect measure of technological knowledge. Despite of that, patent data remain the best standardized proxy of innovative activities and the propensity to patent in the chemical sector is relatively high compared to other sectors. Thus, patents can be considered as relatively good measure of innovation.

4. Results and discussion

4.1 Trends emerging from patent statistics

Fig. 1 displays the evolution over time of SCT patents. We observe that the innovative activity in the field has progressively increased since the end the 1980s and has experienced two periods of sustained growth: in the early 1990s (1991-1994) and in the last three available years (2009-2011). The first period of sustained growth can be interpreted as the emergence phase of SCT and follows the enactment of the first important environmental regulations in the chemical sector (Nameroff et al., 2004). As highlighted by Nameroff et al. (2004), since 1993 there has been far less environmental legislation and the growth of SCT patents has slowed down. The presence of

second period of sustained growth seems to suggest that in the most recent years organizations have considerably intensified their innovative efforts in the field. Fig. 1 also provides the time evolution of SCT patents as percentage of total chemical patents¹². It highlights a slower growth of SCT patents, but the same important increase in the early 1990s and in the last few years. These results suggest that the growth of SCT patents, especially in the two high-growth periods, is only partially due to a more general increase of patenting activity in the chemical sector. However, it is important to note that although the share of SCT patents has doubled in the last 10 years, from 3.1% in 1991 to 6.2% in 2011, still SCT patents represent a relatively low proportion of total chemical patents.

Fig. 1 contains the time evolution of patents granted to research organizations as a share of total SCT patents. We observe that such a share has been rapidly increasing until 2006, experiencing then a slight decline. However, this decline is not due to a reduced activity of research organizations, but rather to a higher growth of firms' patenting activity. These results confirm that, in the most recent years, private companies have considerably intensified their innovative efforts in SCT. In general, the share of patents granted to research organizations remains very important: in 2006, its peak, it was 23.2% out of total SCT patents (it was 2.5% in 1971), and the average value over the whole period is 14.8%. This result highlights the important role played by universities and government agencies as source of knowledge generation and may signal a growth of technological opportunities in the field.

[Insert Figure 1 About Here]

Table 1 shows the distribution of SCT patents among the top 8 technological classes. These results show that most of the innovative activity in the field relates to three broad technological areas: organic chemistry (C07), organic macromolecular compounds, i.e., various types of polymers (C08) and biochemistry (C12). The result relating to organic chemistry is not surprising as its range of application is enormous: organic compounds are important constituents of many chemical products, including petrochemicals, plastics, food, drugs and paints. More interesting are the results relating to the subsequent two technological classes as they highlight two important areas of research of sustainable chemistry. Because of their broad range of properties, both synthetic and natural polymers play an essential role in everyday life. Synthetic polymers are derived from

¹² Following Nameroff et al. (2004), total chemical patents have been computed by including the IPC C, B01 and B04.

petroleum and range from synthetic plastics to synthetic fibers and rubbers. Natural polymers (biopolymers) occur in nature and include cellulose, carbohydrates, proteins, DNA, and other biopolymers produced from biomass that are used to manufacture recyclable or biodegradable plastics (e.g., PLA). Biochemistry deals with the study of chemical processes within and relating to living organisms. This field has made important advances in the design and application of genetically modified enzymes and microorganisms, as well as in the development of alternative catalysts based on natural enzymes (see the Appendix for more details)¹³.

[Insert Table 1 About Here]

Fig. 2 shows the distribution of SCT patents among the top 20 countries. The patent activity in SCT seems to be highly concentrated in the US, which own more than 57% out of total SCT patents. However, this result may be, to some extent, overestimated due to the bias introduced by the use of the USPTO dataset (see section 3). If we look at the other top countries, we observe that, not surprisingly, Japan and Germany come soon after the US, with a percentage of 10.5% and 9.2% out of total SCT patents, respectively. The total share of European countries ranked among the top 20 countries amounts to 20.9%. This makes European countries important players in SCT. Emerging or latecomer countries – Korea, India, Taiwan and China – own a negligible share of SCT patents. This is also confirmed by the country distribution of patents granted in the most recent years (Fig. 2): even if the share of patents owned by emerging countries has slightly increased in the last 10 years, still it remains very low. Therefore, we do not observe any new pattern when we look at the nationality of organizations that are developing SCT. In particular, contrary to what has been observed in other sectors like semiconductors (Epicoco, 2013), emerging countries are not significantly eroding the technological advantage of European countries. This is rather surprisingly, especially if we consider that emerging countries have importantly eroded the competitive advantage of US, Europe and Japan (Cefic, 2013; section 2.2).

[Insert Fig 2 About Here]

13 We also detected the distribution of SCT patents among technological subclasses and got the confirmation that research relating to biochemistry (C12) is focusing in an important way on the development of both new microorganisms/enzymes by using genetic engineering techniques (C12N) and alternative catalysis techniques using natural enzymes (C12P). Indeed, C12N and C12P are the highest-ranked technological sub-classes (10.8% and 7.9% out of total SCT patents, respectively) after C07C (ACYCLIC OR CARBOCYCLIC COMPOUNDS), which is cited by 11.1% out of total SCT patents.

In Fig. 2 we also display the geographical distribution of patents granted to research organizations. We can see that most of the research organizations are based in the US. Even if this result may be to some extent biased by the limitations of our dataset discussed above, still European universities seem to be less active than their international counterparts, in particular German organizations, which only own 1.9% of total patents granted to research organization. Indeed, the share of European public organizations out of total patents granted to public organizations amounts to 14.1%, while as reported above, the total share of European countries out of all SCT patents is 20.9%. In the same figure, patents owned by public organizations are shown as share of national SCT patents. Here we observe that emerging countries present the highest shares. This indicates that while governments from emerging countries are making some efforts to support the development of SCT, private companies do not. This may reflect the lack of both the necessary capabilities for investing in SCT (companies are still far from the technological frontier) and the necessary incentives in terms of environmental regulation and policies.

Finally, Table 2 presents the top 30 patent assignees in the field. Among the most active organizations we find some of the largest and oldest chemical companies, including the US DuPont and Union Carbide¹⁴, and the German BASF, Bayer and Henkel. Quite surprisingly, the second highest ranked assignee is the US government. This is an important signal of the involvement of the US government in the development of SCT. Among the other research organizations we find IFP Energies Nouvelles (the old French Institut du Petrol), some of the most important US universities (University of California, MIT, Michigan State University), and, quite surprisingly, the Council of Scientific and Industrial Research, the India's largest R&D organization. By looking at the remaining organizations, we observe major US oil and gas corporations, including Exxon, Mobil Oil, UOP, Chevron, Texaco, Phillips Petroleum¹⁵, and the Anglo-Dutch Shell. We also find conglomerate corporations like 3M and General Electric, consumer goods companies (Proctor & Gamble), agricultural biotechnology corporations (Monsanto), and life science companies (Hoechst)¹⁶. Thus, even if the innovative activity in the field seems to be spread among a relatively high number of organizations (the top assignee only owns 1.67% out of total SCT patents), the most important

14 Since 2001, a wholly owned subsidiary of Dow Chemical

15 In 1999 Mobil Oil merged with Exxon to form ExxonMobil, in 2001 Texaco merged into Chevron and in 2002 Phillips Petroleum merged with Conoco to form ConocoPhillips.

16 Both Monsanto and Hoechst are former chemical companies. Hoechst is now a subsidiary of Sanofi-Aventis.

patenting organizations result to be large and established chemical companies from the US and Germany, together with the US government and some of the major US oil corporations.

[Insert Table 2 About Here]

In sum, the analysis of patent statistics shows that SCT are emerging slowly and still represent a relatively low proportion of chemical technologies. However, the recent growth in patenting activity (2009-2011) may signal a renewed interest of private firms in the field. Concerning the organizations that generated SCT, patent statistics do not provide evidence for the emergence of new firms. The most important innovative firms are all large incumbents of the industry, based in countries with a strong chemical tradition. These firms have all been created in the XIX century or in the first half of the XX century to exploit the major innovations of the industry mentioned in section 2.2. Many of them have also done fundamental contributions to the development such innovations, which still constitute their core technological base. It seems therefore, from this first analysis, that the emergence of SCT has not significantly eroded the technological advantage of chemical incumbents. However, the important role played by research organizations may signal that technological opportunities are expanding and barriers to entry are lowering. Similarly, the important role played by government agencies suggests that some governments, in particular the US government, are significantly engaged in developing SCT.

4.2 Technological clusters and organizational demography

As detailed in section 3, we used SCT patents and their backward citations to identify the main clusters of SCT. In particular, we calculated all Technological Islands of size between 2 and 250, and found 2331 clusters, which include 8622 patents (31.5% out of total SCT patents). Table 3 provides information on clusters with size equal or greater than 20 vertices. We observe two large Islands (including 249 and 246 patents, respectively) and a few Islands with more than 100 patents. Then, the Islands' size declines very rapidly. The Islands' size frequency distribution is presented in a log-log scale in Fig. 3, which confirms the presence of a few large Islands and a high number of small or very small Islands.

[Insert Table 3 and Figure 3 About Here]

In order to provide an indication of the technological areas where organizations are concentrating their research efforts, we analyzed, with the assistance of an expert¹⁷, the topic of patents involved in the largest Islands (Table 3). Table 3 also displays the average publication year of clusters, which provides an indication of their average “age”. The “oldest” Islands deal with extraction and separation methods from petroleum (Islands N°3, 15, 22), asbestos-free materials for vehicles and industrial machinery (Island N°12), and environmentally-friendly adhesives and coatings (Island N°11). The most recent clusters relate to biopolymers and bioplastics (Island N°1), chemical and biochemical microreactors (Island N°8), biochemistry (Island N°10) and different biodegradable or non-toxic compounds (Island N°4, 9, 14, 19, 20). In between, we find clusters concerning biochemistry (Island N°2) and a variety of more environmental-friendly materials and processes with applications in electronics, telecommunication, paper industry, pharmaceuticals, food, etc. (Island N°5, 6, 7, 16, 18, 21)¹⁸. These results suggest that research relating to broad field of biochemistry, including biopolymers extracted from biomass, biological methods and biological microreactors, has acquired a growing importance, while research on petroleum processes seems to have lost weight.

To provide a better understanding of the inner structure of clusters, we extracted the three largest Islands and applied to them a number of algorithms that allow identifying the patents, and the corresponding organizations, that have been most influential in enabling the development of the cluster. Fig. 4 shows Island N° 1, which, as mentioned before, deals with the development of biopolymers extracted from biomass to make environmentally degradable plastics (bioplastics)¹⁹. If we start from the bottom of the figure and move along the vertical axis, we can follow the time evolution of the cluster. The size of vertices and the thickness of arcs correspond to the relative importance of patents and citational links, respectively (as revealed by traversal weights on arcs). The cluster sprout from a patent granted in 1975 to Union Carbide, an important US chemical company founded in 1917. The subsequent developments, in the second half of the 1970s and in the 1980s, were disclosed by two main organizations: Coloroll, at that time a young firm active in the home furnishings business, and the US government. The 1990s, which begin with the Warner-

17 Enrico Burello (TNO)

18 Islands N° 13 and 17 deal with pharmaceuticals products, but we did not find any explicit environmental claim.

19 Petroleum based plastics are hardly degradable, non renewable and responsible of CO₂ emissions, whereas biomass based plastics are degradable, renewable and potentially carbon neutral. Applications of these materials include replacement of plastic materials in packaging, coating, textiles, and in many consumer goods. Patents in this Island focus especially on methods for synthesizing or blending polylactide (PLA), which is one of the most important bioplastics.

Lambert patent, are then dominated by Cargill, a large US multinational corporation founded in 1865, mainly active in the food and commodity sectors. The most recent developments of the Island (2000s) seem to show a wider variety of organizations at work, including research organizations (Michigan University) and younger firms active in the field of bioplastics and biodegradable packaging (the German BIOTEC and the US Khashoggi Industries). It seems therefore that a relatively high variety of organizations contributed to the development of this cluster: large and established companies, research organizations and, especially in the most recent years, more specialized and younger firms.

[Insert Figure 4 About Here]

The second largest Island, which relates to the development of biological methods for processing and recycling waste²⁰, is displayed in Fig. 5. Here we observe a higher degree of organizational continuity, in particular because of Air Products and Chemicals patents, which are spread all over the Island. Air Products and Chemicals is an international corporation founded in 1940, whose principal business is selling gases and chemicals for industrial uses. The graph also shows the presence of other large and established firms (Union Carbide, Celanese Corporation, Siemens, Bacardi, AECI), and an important number of research organizations (US government, Polytechnic University, Institute of Gas Technologies, Iowa State University). Like in the previous Island, there seems to be some evidence, in the most recent years, for a more active role of smaller and younger firms active in the engineering and biotechnology sectors (Bioprocess Engineering, Gist-brocades, Khudenko engineering).

[Insert Figure 5 About Here]

The third Island concerns different aspects of extraction and separation processes of petroleum²¹, and, as we can observe in Fig. 6, shows a high degree of organizational continuity: most of the patents are owned by two large companies active in the petroleum sector, namely Mobil Oil and UOP. The roots of both companies date back to the early 1900s, and UOP has given a

²⁰ Such methods are based on the action of bacteria that break down the compounds into simpler chemicals.

²¹ It concerns, in particular, the development of processes and apparatuses for fluidized catalytic cracking (FCC), which is the process by which hydrocarbons from petroleum are broken down into simpler chemicals used for producing fuel or as building blocks for making plastics.

particularly important contribution to the development of current refining technologies. Neither public organizations nor smaller, specialized firms played a role in the development of this cluster.

[Insert Figure 6 About Here]

It seems therefore, from this preliminary analysis of organizational demography, that although large incumbents show an important continuity in their innovative activity, this is less strong in the most recent clusters and years, where younger firms and research organizations acquire a greater role. In order to provide systematic evidence on the respective role played by incumbents and new firms in SCT, we gathered data about the date of creation of all firms that have been granted of patents in our clusters. We consider a firm as a new organization if the time between its date of creation and the date of application of the patent is less than 11 years²². The procedure to establish the date of creation of firms takes into account both ownership relations between organizations (e.g., mother- and daughter-firms) and mergers, acquisitions, split-ups²³. Therefore, in this work, new firms are all independent companies that were less than 11 years old when they applied for a SCT patent. As shown in Table 4, only 6.92% out of total SCT patents were generated by new firms, less than patents generated individuals (7.42%). The great majority of SCT patents (61.49%) were indeed granted to established firms. Research organizations also detain an important share of patents, as already emerged from the analysis of patent statistics.

These results confirm what the analysis of patent statistics had already suggested, i.e., that SCT have not stimulated in a significant way the emergence of new firms and have not significantly eroded incumbents' advantage. We may deduce that SCT have not triggered any significant technological ferment in the chemical sector and that the innovative activity in the field is mainly following a pattern of "creative accumulation". However, a number of studies have highlighted empirical cases in which incumbents were the source of major innovations (e.g., Methe et al., 1996; Bergek et al., 2013; Berggren et al., 2015) and, in any case, we cannot exclude *a priori* that incumbents, in developing SCT, are pursuing a more radical innovative strategy than new firms.

22 We used the year of application of the patent as a proxy for the year when the invention was completed.

23 Therefore, if, at the year when the patent was applied, a company was a subsidiary (or a division) of an older company, we assigned the date of creation of the older company. Similarly, if the company, at time when it applied for the patent, had merged with an older company (or it was the result of the merger of two older companies), we used the date of creation of the older company. However, if a company was acquired by an older company after the application of the concerned patent, we kept the date of creation of the younger company, because when it was working at the concerned invention, it was still an independent company. Data were gathered by the author using different sources, including the web-page of companies and the datasets Factiva, Bloomberg and Orbit.

Therefore, we now examine some properties of organizations' knowledge base that are expected to capture aspects of radicalness of involved technologies.

The results are reported, for each organization type and for the whole sample, in Table 4²⁴. We observe that, according to all our measures, new firms have higher average scores than established firms. This means that technologies generated by new firms rely more on the contribution of scientific knowledge (SCIENCE), are broader (WIDTH), more diversified (SCOPE) and more original (ORIGINALITY) than technologies generated by established firms. As discussed in section 3, those measures are associated by the literature with more basic, complex, radical and valuable inventions, as well as with higher technological opportunities. The SCIENCE score of new firms is particularly high: more than twice the score of established firms and just slightly inferior to that of research organizations, which, as expected, have the highest score. Following Trajtenberg et al. (1997), we tested for the statistical significance of differences in the means of the measures between different organization types²⁵. The difference between the means of new and established firms is statistically significant for all our measures. The same holds for the difference between the means of established firms and research organizations. New firms' patents also have the highest score of WIDTH and ORIGINALITY, but the difference *vis-à-vis* other organization types is less important for the originality index and the difference between the means of new firms and research organizations is not significant for ORIGINALITY. Interestingly, in studying the difference between university and corporate patents, Trajtenberg et al. (1997) found that, contrary to what expected, universities do not have a significantly higher ORIGINALITY score than corporations. Here we found, that although universities and government agencies do not have a significantly higher ORIGINALITY score than new firms, they do have a significantly higher score than established firms. Moreover, we found that research organizations have a significantly more diversified knowledge base (SCOPE) than established firms, but not than new firms, since the difference between the means of new firms and research organizations is not significant for the SCOPE measure²⁶.

[Insert Table 4 About Here]

24 The whole sample also includes 876 missing observations, which are all firms for which we were not able to find any reliable information on their date of creation.

25 We performed both a t-test and a Wilcoxon rank-sum test (WMW test), because our normality test rejected the null hypothesis that there is no significant departure from normality. Both tests gave the same results.

26 The difference between the means of new firms and research organizations is instead significant for the SCIENCE and WIDTH measures.

In conclusion, new firms have given a relatively marginal contribution, in quantitative terms, to the development of SCT. However, such a small group of new organizations seems to have a higher potential to break with existing knowledge in the chemical industry and to generate radically new environmental innovations. Therefore, as a last step, we analyzed more in detail the characteristics of these new firms. We found that the importance of new firms in generating SCT has grown since the emergence of SCT: as shown in Fig. 7, in 1990 new firms patents were only 2.9% of total patents granted to firms, while in 2011 they reach 21.3%. We also found that the great majority of these new firms (77%) are based in the US²⁷ and that their most important areas of research (Table 5) are biotechnology, pharmaceuticals, material chemistry and chemical engineering. The analysis of technological classes and sub-classes of new firms' patents also confirms that biochemistry and biotechnology is their main area of research²⁸. These results, indicate that, in the most recent years, younger and more specialized US firms, mainly active in the broad field of biochemistry, have started to weaken the technological advantage of industry incumbents. These conclusions, which seem to be coherent with similar findings for the green energy sector (Breitzman and Thomas, 2011), suggest that, if supported by effective policies, technological ferment in the field, which at the present appears relatively limited, has a potential of growth.

[Insert Figure 7 and Table 5 About Here]

27 US firms are followed, at great distance, by Canada, Great Britain and Germany with 5.1%, 4.6% and 4%, respectively.

28 C12 (BIOCHEMISTRY; BEER; SPIRITS; WINE; VINEGAR; MICROBIOLOGY; ENZYMOLOGY; MUTATION OR GENETIC ENGINEERING) is the highest cited technological class (35,6% of new firms patents) and C12N (MICRO-ORGANISMS OR ENZYMES; COMPOSITIONS THEREOF; PROPAGATING, PRESERVING, OR MAINTAINING MICRO-ORGANISMS; MUTATION OR GENETIC ENGINEERING; CULTURE MEDIA) is the highest cited technological sub-class (19.6% of new firms patents)

5. Conclusions

The generation and diffusion of radically new environmental innovations is considered increasingly important in order to cope with current sustainability challenges. Yet, assessing the innovative potential of emerging environmental technologies remains difficult. Using an original dataset of patents, this paper provides, for the first time, a comprehensive analysis of environmental innovation in the chemical sector. We found that SCT are emerging slowly and still represent a relatively low proportion of chemical technologies. Our analysis also shows that SCT have not stimulated, in a significant way, the emergence of new firms. New firms have given a relatively marginal contribution, in quantitative terms, to the development of SCT over our 40-years analysis, while the most important innovative firms are all large, established chemical and petroleum company based in countries with a strong chemical tradition. Even firms from emerging countries, which have importantly eroded the competitive advantage of US and European firms (Cefic, 2013), played a negligible role in developing SCT. These results suggest that the emergence of SCT have not triggered any significant technological ferment in the chemical sector and that incumbents' advantage in the industry remains strong. It seems, therefore, that environmental innovation in the chemical sector is mainly following a pattern of “creative accumulation”, in which incumbent firms elaborate and adapt their existing technologies in order to incrementally improve the environmental performance of their products end processes.

We should conclude that, in the chemical sector, the potential of generating radically new environmental innovations is still limited. However, three elements of our analysis bucked the general pattern observed and allow mitigating such conclusion. First, in the last three (available) years (2009-2011), firms have considerably intensified their innovative efforts in the field. This may signal a renewed interest in SCT. Second, research organizations have given an important and increasing contribution to the generation of SCT. This may indicate that technological opportunities in the field are expanding and barriers to entry are lowering. Moreover, the important role played by government agencies in generating SCT suggests that some governments, and in particular the US government, are supporting the development of such technologies. Third, the importance of new firms has been growing in the last years. Moreover, new firms seem to have a higher potential to break with existing knowledge in the chemical sector and to generate radically new innovations. Indeed, our analysis shows that technologies generated by new firms are broader, more science-

based, diversified and original than technologies generated by established firms. These properties are associated by the literature with higher technological opportunities and with more basic, radical, complex and valuable inventions (see section 3). It seems, therefore, that in the most recent period, a small group of younger and more specialized firms, mainly based in the US and active in the broad field of biochemistry, has started to weaken the technological advantage of industry incumbents. These results suggest that, if supported by effective policies, technological ferment in the field has a potential of growth.

Although these findings are subject to a number of caveats (see section 3), they provide important contributions to extant literature. First, innovation scholars have shown since long time that innovation patterns differ across sectors (Pavitt, 1984; Malerba, 2002). By providing a comprehensive analysis of environmental innovation in the chemical sector, this paper contributes to improve our understanding of the innovative dynamics triggered by emergent environmental technologies in this important sector. Second, by analyzing the differences in the knowledge bases of organizations that generated SCT, this paper contributes to the literature streams examining the respective capabilities and roles of incumbents and new firms in innovative processes (see section 2.1). Consistently with this literature, we found that new firms' technologies display a higher degree of radicalness than established firms' technologies. To our knowledge, none of the previous studies has tried to compare the degree of radicalness of incumbents' and new firms' technologies. Finally, this work also contributes to sustainability transitions studies. By building an original dataset of patents relating to SCT, we provided a deep analysis of the main technologies and organizations involved in this emerging domain. Coherently with sustainability transitions research, we found that most of environmental technologies in the chemical sector were generated by established firms and that these technologies are less radical than new firms' technologies. These results provide empirical evidence on the importance, in current economic systems, of the path-dependence and lock-in phenomena highlighted by transitions studies. Moreover, our analysis also allowed identifying a small group of new organizations with a higher potential of challenging established technologies and generating those radical environmental innovations that are at the core of sustainability transitions.

These conclusions call for effective policies supporting the generation of radically new environmental innovations. As highlighted by Smith (2009), despite widespread environmental innovation efforts and incentives, most of current environmental policies tend to promote

incremental changes in existing technologies that have limited environmental benefits. Different policy measures may be suited for stimulating radical innovation. Funding basic and explorative research aimed at building the scientific and technological foundations of sustainability may be particularly important in order to create a broader set of radically new technological opportunities. This is especially important for European countries, whose universities showed to be less active than their international counterparts. Supporting new firms' innovative projects and niche experiments may also be particularly important for encouraging radical innovation. As highlighted by strategic niche management studies (e.g., Kemp et al., 1998), support may take different forms, depending on the barriers faced by each specific technology, and may include: enacting and stimulating the generation of sufficient knowledge about problems, needs and possibilities of new technologies, formulating shared long-term goals, providing financial support, directly or through public procurement, introducing the necessary changes in the broader institutional framework, coordinating and shaping actor expectations and strategies toward shared desirable directions. Critical aspects of such policies, which warrant further research, concern the choice of the type, the variety and the duration of experiments to support. In that respect, we share the view that it is important to promote technologies with high opportunities for improvement and wide range of applications, to take a long-term perspective and to create sufficient "critical mass" to allow sustainable technologies becoming competitive.

More in general, the emergence and diffusion of radically new environmental technologies require important changes in both the supply and demand sides as technologies are embedded in wider economic and social structures. Therefore, changes in consumption patterns, public consciousness and pressure may importantly help to make clear the need for radical environmental innovations and open up new opportunities. We also believe that making clear the urgent need of developing radical environmental technologies should be an important task of governments. If coupled with adequate financial and organizational resources, a clear and reliable political commitment to develop radical environmental technologies may operate as "focusing device" (Rosenberg, 1969) of both research and productive efforts, accumulating them toward sustainability targets.

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Tables and Figures

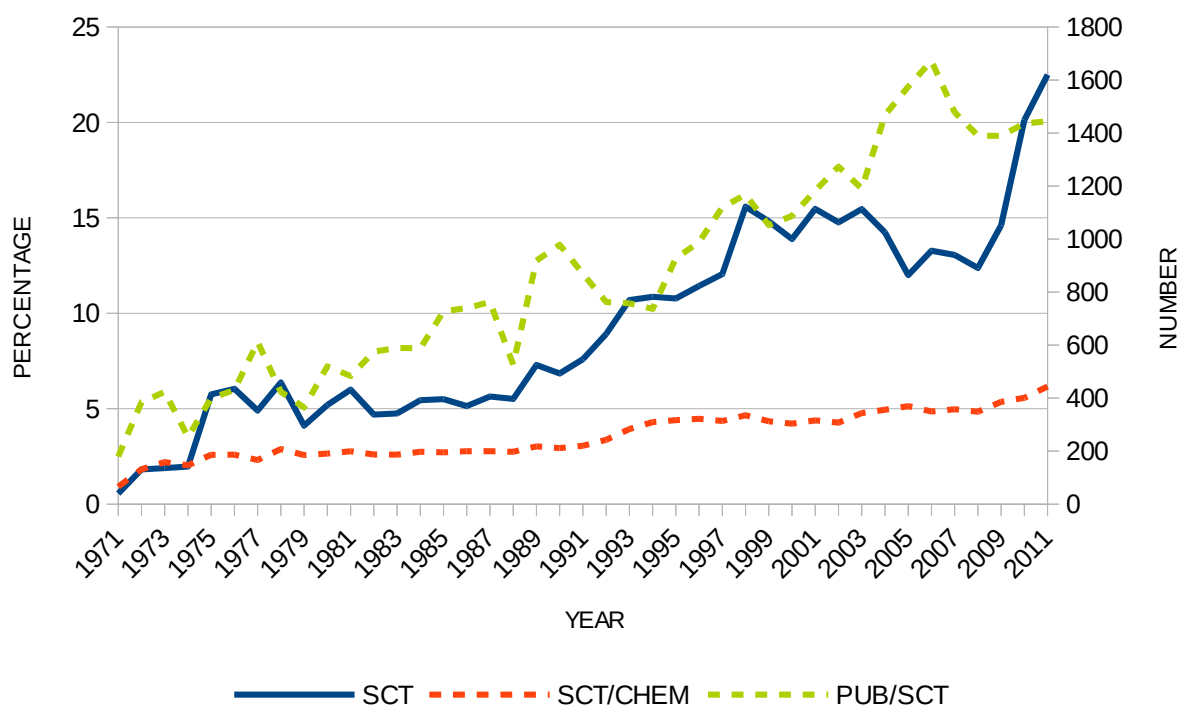


Fig. 1. Evolution over time of SCT patents (total number and percentage of total chemical patents) and of SCT patents granted to research organizations (percentage of total SCT patents). Patents granted by the USPTO by publication year.

Table 1. Distribution of SCT patents among technological classes²⁹

TECHNOLOGICAL CLASS	% OF 27355
C07: ORGANIC CHEMISTRY	26.4
C08: ORGANIC MACROMOLECULAR COMPOUNDS; THEIR PREPARATION OR CHEMICAL WORKING-UP; COMPOSITIONS BASED THEREON	20.2
C12: BIOCHEMISTRY; BEER; SPIRITS; WINE; VINEGAR; MICROBIOLOGY; ENZYMOLOGY; MUTATION OR GENETIC ENGINEERING	18.8
B01: PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL	13.0
A61: MEDICAL OR VETERINARY SCIENCE; HYGIENE	8.6
C10: PETROLEUM, GAS OR COKE INDUSTRIES; TECHNICAL GASES CONTAINING CARBON MONOXIDE; FUELS; LUBRICANTS; PEAT	6.3
C09: DYES; PAINTS; POLISHES; NATURAL RESINS; ADHESIVES; COMPOSITIONS NOT OTHERWISE PROVIDED FOR; APPLICATIONS OF MATERIALS NOT OTHERWISE PROVIDED FOR	5.7
C02: TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE	5.1

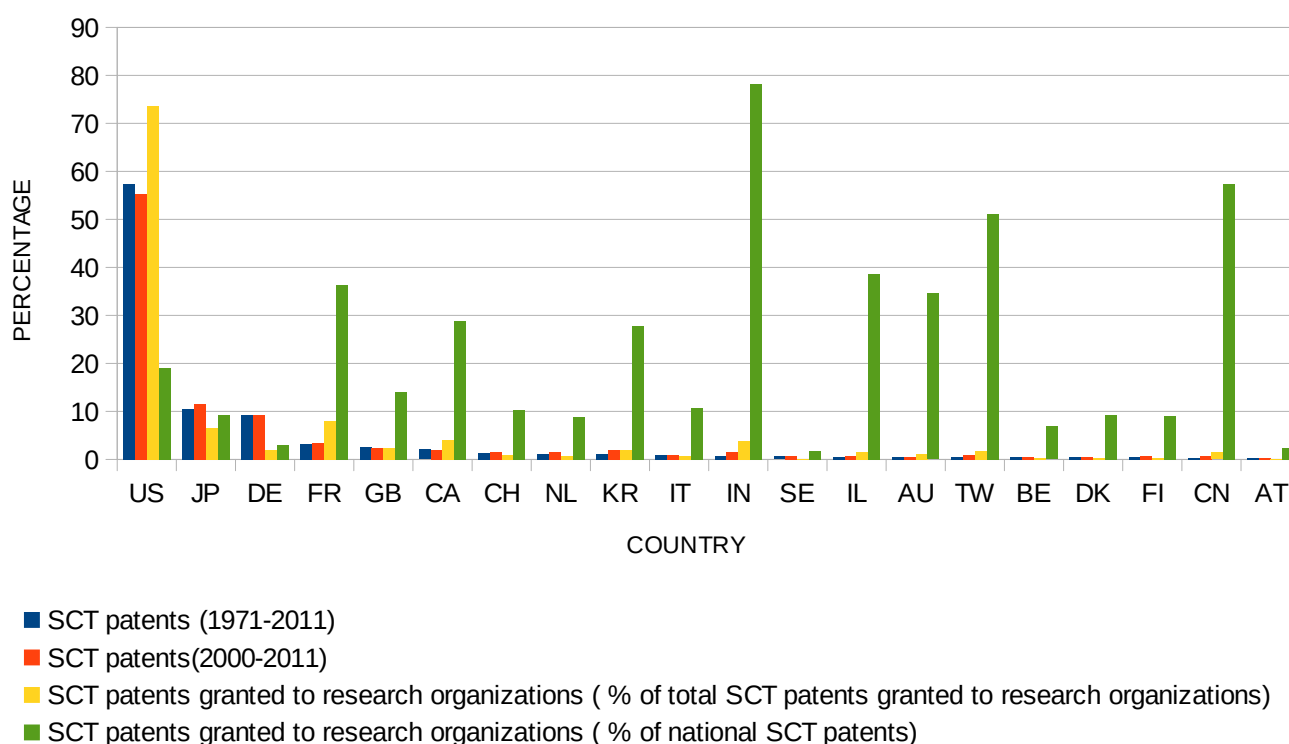


Fig. 2. Geographical distribution of total SCT patents and of SCT patents granted to research organizations³⁰

29 Patent counts are whole counts: all technological classes cited by each patent in the dataset have been taken into account.

30 Patent counts are whole counts: individual companies are credited with a patent even if several companies are listed

Table 2. Top patent assignees in the field of SCT³¹

ORGANIZATION NAME	TOTAL COUNT	% OF 27355
DuPont	458	1.67
USGOV	424	1.55
BASF	388	1.42
Bayer	301	1.10
3M	214	0.78
Exxon	214	0.78
Proctor & Gamble	206	0.75
Union Carbide	206	0.75
Mobil Oil	196	0.72
UOP	194	0.71
IFP Energies Nouvelles	175	0.64
Monsanto	171	0.63
Henkel	148	0.54
Hoechst	148	0.54
Chevron	145	0.53
General Electric	143	0.52
Council of Scientific and Industrial Research	141	0.52
University of California	136	0.50
Texaco	135	0.49
Mitsubishi	133	0.49
Degussa	131	0.48
Phillips Petroleum	130	0.48
Shell	129	0.47
Dow Chemical	119	0.44
Ciba Geigy	102	0.37
Massachusetts Institute of Technology	102	0.37
Michigan State University	100	0.37
ExxonMobil	99	0.36
Boehringer Ingelheim	92	0.34
Canon	87	0.32

as co-assignees. The country statistics are calculated considering the address of each patent assignee.

31 The procedure to draw up this list is based only on the name of the patent assignee listed on the patent and do not take into account ownership relations between organizations (e.g. mother- and daughter-firms), or mergers, acquisitions and split-ups. As an exception to this rule, it was decided to create a category that unites all different US government organizations, such as a ministry or the army (universities are not included here). This category is called "USGOV". Moreover, the names of patent assignees have been normalized by the author for taking into account the use of different names for the same company (e.g., IBM and International Business Machines Corporation).

Table 3. Technological clusters

ISLAND N°	ISLAND SIZE	AVERAGE YEAR OF PUBLICATION	ISLAND TOPIC
1	249	1998.9	Biopolymers to make environmentally degradable plastics
2	246	1994.7	Biological methods for processing and recycling waste
3	142	1990.8	Extraction and separation processes of petroleum (FCC)
4	123	1998.6	Materials that are free of lead and toxic metals (e.g., cadmium) with applications in semiconductors, electronics and electronic components
5	107	1996.3	Materials that are free of lead and toxic metals (e.g., cadmium) with applications in electronics, imaging, projection, telecommunication
6	102	1994.3	Environmentally improved processes for bleaching lignocellulosic materials (chlorine free bleaching processes) in paper industry
7	98	1995.2	Non-toxic gases, explosives, pyrotechnics
8	89	2002.4	Chemical and biochemical microreactors
9	71	1999.4	Biodegradable, environmentally-friendly fluids used in drilling operations for extraction of oil or gas, or as lubricants, surfactants and detergents for industrial machines
10	50	2001.2	Methods for molecular biological reactions, analysis and diagnostics
11	45	1991.7	Environmentally-friendly adhesives and coatings
12	44	1987.1	Asbestos-free materials (e.g., friction materials for vehicles and industrial machinery)
13	43	2001.2	Pharmaceutical compounds active as antiviral agents
14	41	2000.7	Biodegradable compounds used in tissue engineering
15	38	1989.7	Alternative extraction methods: supercritical fluids
16	31	1995.4	Improved methods for preparing Polyol fatty acid polyester for use in food, beverage, pharmaceutical, and cosmetic applications
17	27	1999.5	Pharmaceutical compounds
18	27	1996.0	Methods to reduce pollutants in the exhaust gases produced from the combustion of fuel (e.g., in vehicles) and to clean air from pollution (e.g., filters)
19	23	1999.1	Biologically active peptides with reduced toxicity for controlling pests
20	22	2005.2	Processes of reduced or no toxicity for forming metal nitride (MN)
21	21	1997.4	Non-toxic, non-flammable, safe compositions of biodegradable components for removing and stripping paint, varnishes and stains
22	20	1989.4	Environmentally improved methods for extraction and separation from petroleum
Total	1659	1996.5	

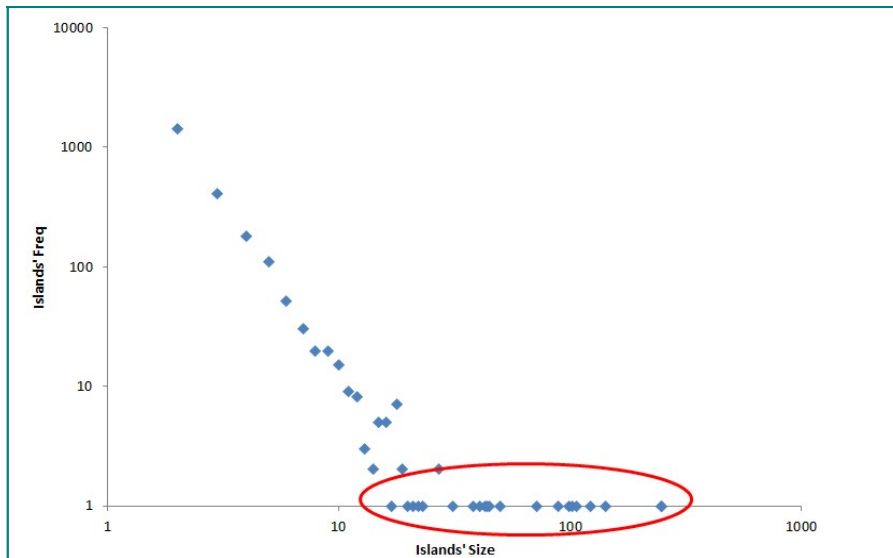


Fig. 3. Islands' size frequency distribution (log-log scale)

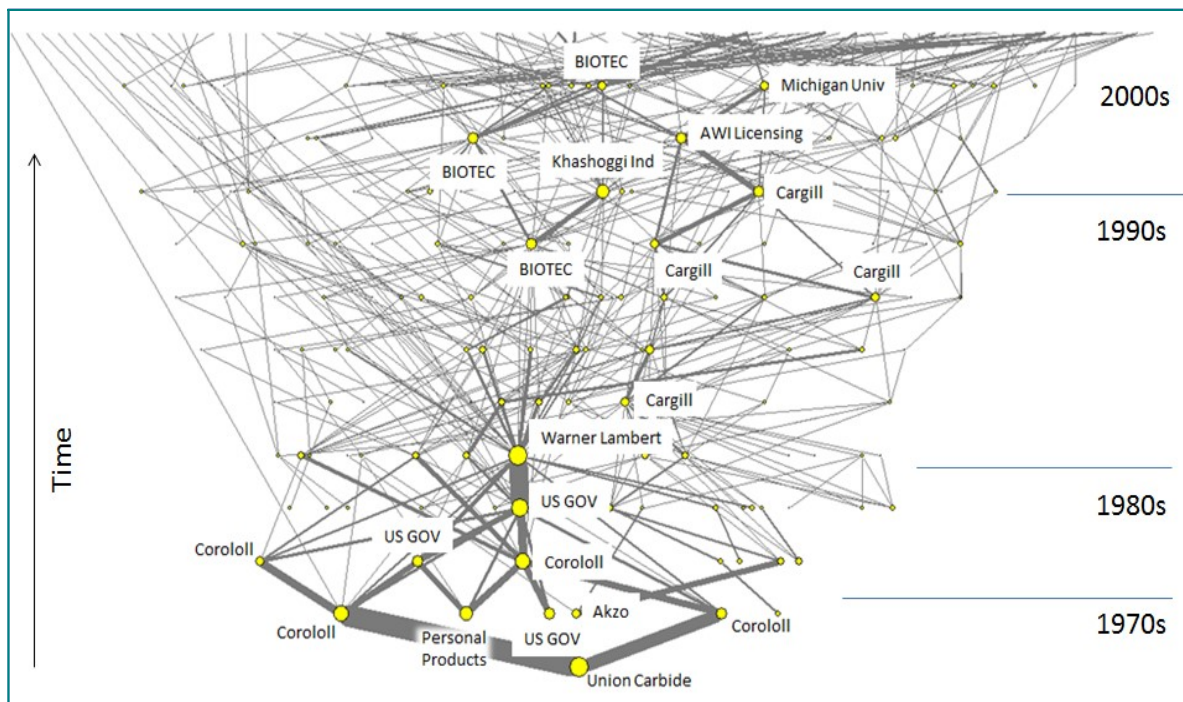


Fig. 4. Island N°1: Biopolymers to make environmentally degradable plastics

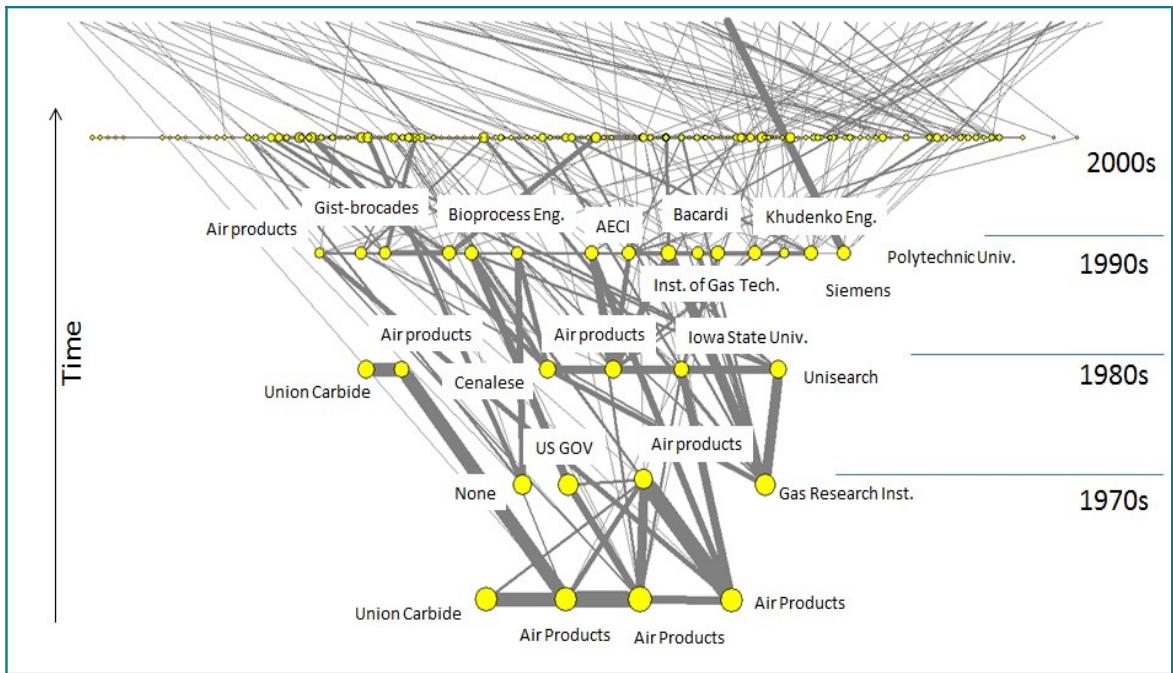


Fig. 5. Island N°2: Biological methods for processing and recycling waste

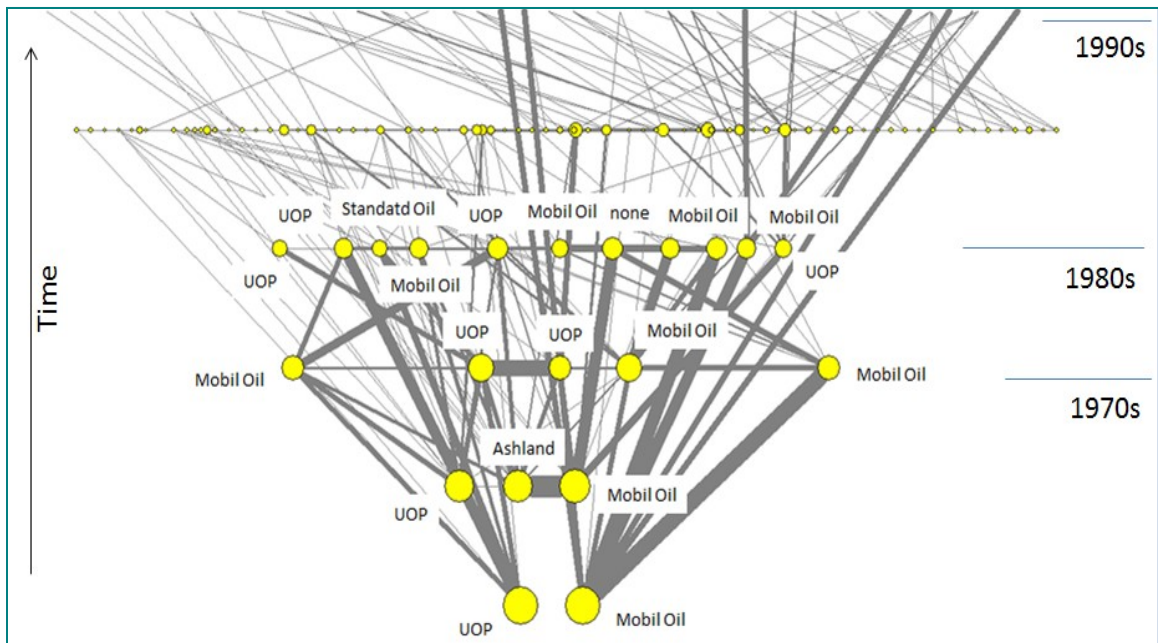


Fig. 6. Island N°3: Extraction and separation processes of petroleum (FCC)

Table 4. Organizational demography

	INDIVIDUALS	NEW FIRMS	ESTABLISHED FIRMS	RESEARCH ORGANIZATIONS	ALL SAMPLE
# PATENTS	651	607	5393	1243	8770
% OF TOTAL PATENTS	7.42	6.92	61.49	14.17	100
SCIENCE					
Mean	0.13	0.34	0.16	0.40	0.20
SD	0.22	0.31	0.22	0.33	0.27
Min	0	0	0	0	0
Max	1	1	1	1	1
WIDTH					
Mean	17.10	23.70	18.07	19.94	18.73
SD	13.42	19.93	15.18	15.40	15.52
Min	1	1	1	1	1
Max	108	139	207	111	207
SCOPE					
Mean	1.45	1.67	1.51	1.73	1.55
SD	0.79	0.89	0.80	0.94	0.84
Min	1	1	1	1	1
Max	7	7	12	8	13
ORIGINALITY					
Mean	0.73	0.73	0.66	0.71	0.68
SD	0.23	0.22	0.27	0.28	0.27
Min	0	0	0	0	0
Max	1.56	1.69	1.71	1.68	1.71

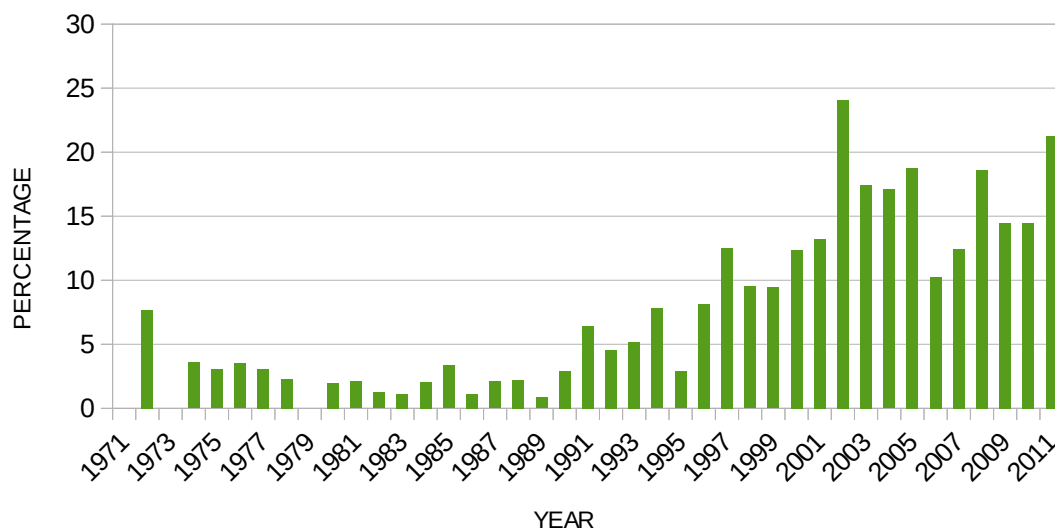


Fig. 7. Evolution over time of SCT patents granted to new firms as percentage of total SCT patents granted to firms

Table 5. Distribution among technological fields of SCT patents granted to new firms³²

TECHNOLOGICAL FIELD	% of patents granted to new firms
Biotechnology	28.3
Pharmaceuticals	24.2
Basic materials chemistry	21.3
Chemical engineering	20.6
Macromolecular chemistry, polymers	17.6
Organic fine chemistry	17.3
Environmental technology	13.2
Analysis of biological materials	10.9
Materials, metallurgy	10.2
Medical technology	9.2

³² Technological fields have been extracted by the patent dataset Orbis. Each patent can be assigned to multiple technological fields. We have taken into account all of them.